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# Direct measurement of the current and power in the load loop of high -frequency electrotechnological devices using the Rogovsky coil

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**Abstract.** The article describes the power supply system of induction furnace based on a semiconductor converter, in which it is possible to work simultaneously in the exciting mode of low-frequency currents and frequencies three times higher when switching the compensation circuit of the furnace inductor at different stages of metal melting. Calculations of electromagnetic processes have shown the advisability of operating the power supply system in the mode of tripling the current frequency at the stage of heating and melting of the metal, but in the mode of low frequency - at the stage of technological processing of the melt. The ratio between the parameters of the furnace power supply in various operating modes are established.

**Keywords:** Rogovsky coil, high-frequency converters, inductors, magneto-hydrodynamic (MHD) devices, induction heaters, melting furnaces.

## 1. Introduction

Inductors of MHD installations, induction heaters and melting furnaces are often powered by frequency converters. The frequency range of currents flowing through the inductors is in the range from fractions of Hz to several MHz. Sensors and devices used in industry for measuring electric current and power usually operate in a fairly narrow frequency range. High-frequency sensors are very expensive and often their design does not allow them to be integrated into the power supply system of induction installations, if this was not provided for during its manufacture. This problem often occurs when conducting experiments and simulating processes in research and training laboratory facilities, when verifying numerical models, and in physical modeling. The use of mass-produced sensors for these purposes is often difficult due to the fact that the measuring system during the experiment must be mounted on rigid non-disassembled busbars. An important condition is also the low price and availability of components of the measuring device.

## 2. Statement of the problem

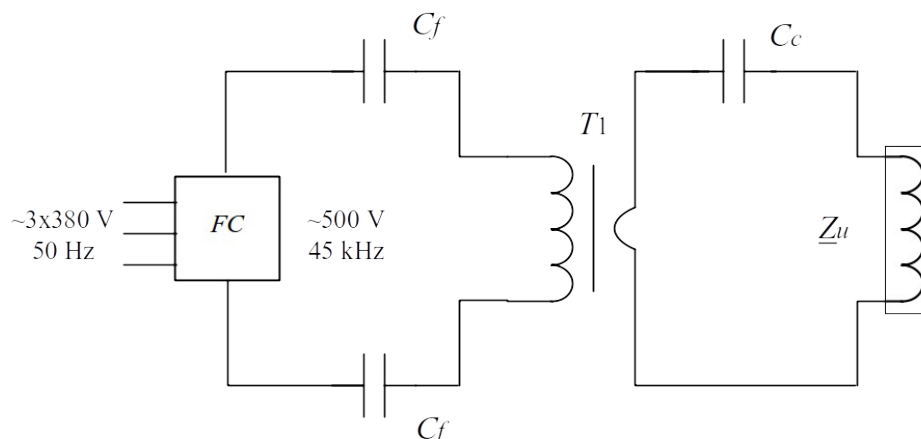
The problem of direct measurement of current and power arose during the research of a laboratory induction melting plant, the scheme of which is shown in Fig. 1.

Traditionally, in such installations, power is measured in the direct current link of the frequency converter (FC), but the measured power includes losses in the semiconductor devices, the busbars, and the matching transformer. The value of the inductor current can be determined by calculating the value of the voltage drop on the compensating capacitor or by recalculating the measured current of the inverter through the transformation coefficient of the



matching transformer. However, both methods are indirect and their accuracy depends on the accuracy of determining the parameters of the elements used in the measurements.

When measuring a large current directly, a method is usually used to measure the magnetic fields that occur near the conductor through which it flows.



**Figure 1.** Electrical diagram of the device under study:

$FC$  - frequency converter;  $C_f$  - filter capacitor;  $C_c$  - compensating capacitor;  $T_1$  – high frequency matching transformer;  $Z_u$  – the impedance of the inductor/

Magnetic fields occupy an important place in physics and engineering. In table 1 the main methods and sensors for measuring these fields are given [1].

**Table 1.** Comparative characteristics of magnetic field sensors

Sensor type	Advantages	Disadvantages
Induction probe	<ul style="list-style-type: none"> <li>simple design;</li> </ul>	<ul style="list-style-type: none"> <li>variable magnetic fields are registered only;</li> <li>a large errors at high frequencies and in strong pulse fields;</li> </ul>
Rogovsky coil	<ul style="list-style-type: none"> <li>simple design;</li> <li>the EMF value does not depend on the current distribution across the contour section;</li> </ul>	<ul style="list-style-type: none"> <li>the sensor winding must be sectioned at high frequencies;</li> <li>difficulties in registering short pulses;</li> </ul>
Ferromagnetic probe	<ul style="list-style-type: none"> <li>relative ease of manufacturing;</li> <li>high stability of operation;</li> </ul>	<ul style="list-style-type: none"> <li>can be used for weak magnetic fields only;</li> <li>signal amplification is required;</li> </ul>
Hall effect	<ul style="list-style-type: none"> <li>records constant and variable magnetic fields in a wide frequency range;</li> <li>compactness;</li> </ul>	<ul style="list-style-type: none"> <li>a stable power supply is required;</li> <li>low-noise amplifier is required.</li> </ul>

One approach to measuring high currents is to estimate their magnitude by the magnetic field that occurs around a conductor with a current. These measurements are non-contact, which is extremely important in the case of high voltages and high currents. The magnetic field of a current that changes over time can be measured using an induction field sensor. However, it is only possible to associate a magnetic field measured at a single point with a current in rare cases when the connection of the magnetic field with the current in a

conductor is well known, for example, in a long solenoid. If you measure the current flowing through a conductor of a complex cross-section, it is extremely difficult to establish this relationship. For pulsed and high-frequency currents, the problem is compounded by the inhomogeneous distribution of current density across the cross section due to the skin effect.

For these reasons, an integral inductive sensor, called the Rogovsky coil, is widely used [3, 4, 6-10]. According to the second Maxwell equation in integral form, the total current  $I_t$  through a pad bounded by a closed loop  $L$ , is associated with the circulation of a magnetic field along the boundary of this loop:

$$I_t = I_c + I_s = \oint_L \mathbf{H} d\mathbf{l} \quad (1)$$

where  $\mathbf{H}$  - is the magnetic field strength vector,  $I_c$  and  $I_s$  - are the conduction and displacement currents through the closed loop  $L$  [1].

Measurements of the alternating magnetic field are usually performed at relatively low frequencies, when the characteristic dimensions of the conductor and circuit are much smaller than the wavelength of electromagnetic radiation. Under these conditions

$$I_t \approx I_c \quad (2)$$

Measuring the tension integral (1) allows you to determine the value of the conduction current. It is possible to replace the contour integral with a sum along the contour:

$$I_c \approx \sum_i H_i \cdot \Delta l_i \quad (3)$$

where the vectors  $\Delta l_i$  form a closed polyline approximating the contour  $L$ . To determine the conduction current, it is possible to measure the magnetic field at a large number of points located evenly along the contour, and then use the expression (3).

Since the circulation of the magnetic field in the right part of expression (1) is determined only by the total current through the cross section, the EMF taken from the Rogovsky coil does not depend on the current distribution over the cross section of the contour  $L$ .

Consider the case when the Rogovsky belt is made on a frame of a dielectric tube with radius  $r$ , which forms a ring with radius  $R$ . The winding is performed evenly, and the total number of turns is equal to  $N$ . Using (3), it is possible to calculate the value of the current derivative over time

$$\frac{di}{dt} = \frac{2R \cdot \varepsilon(t)}{r^2 \mu_0 N} \quad (4)$$

as a function of the EMF  $\varepsilon$ , that occurs on the sensor.

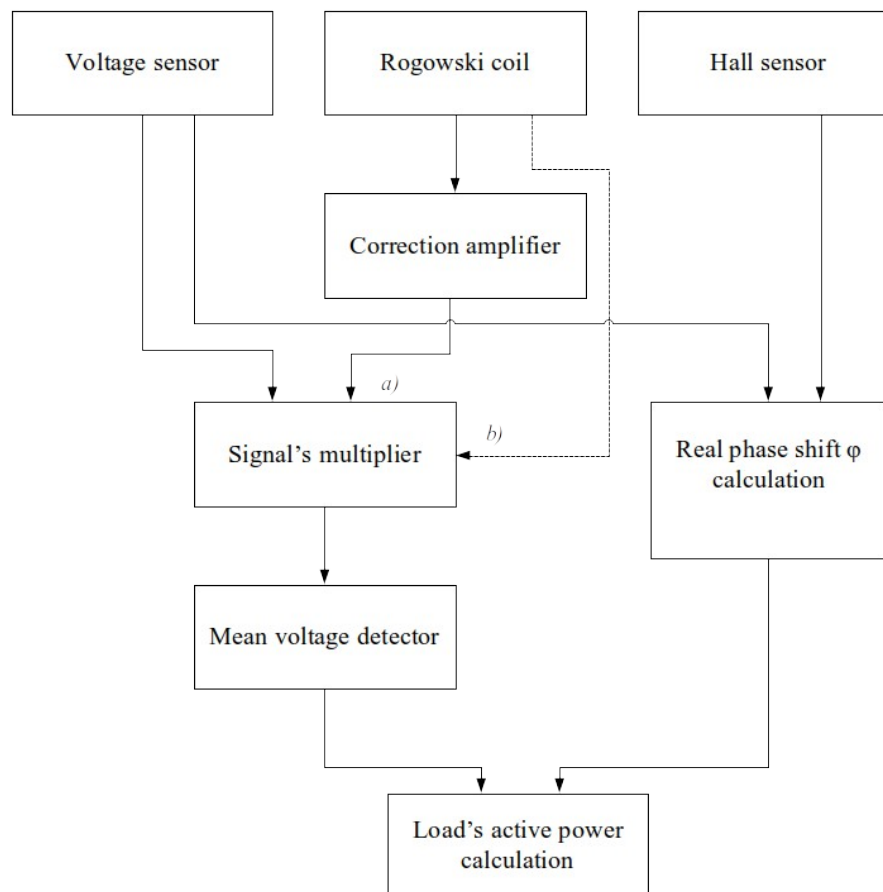
The disadvantage of the Rogovsky coil for direct measurement of currents in high-frequency induction installations is the frequency dependence of the EMF obtained on its conclusions. Therefore frequency correction of the received signal to use this sensor is required [5, 9].

The correction circuits used with the sensor have a non-linear frequency response. Thus, when correcting, it is possible to obtain the signal amplitude and shape with sufficient accuracy, but the initial phase of the received signal may differ from the initial phase of the current that creates a magnetic field near the conductor. The use of phase-correcting circuits complicates the overall scheme and reduces its accuracy. This makes it impossible to use only the Rogovsky coil with a corrective amplifier as the primary current sensor in a direct power

measurement system in HF circuits. To obtain an accurate signal of the current phase, it is proposed to use a Hall sensor.

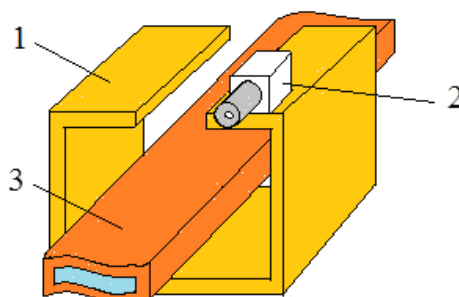
### 3. The description of the design and measurement algorithm

The block diagram of the measuring device is shown in Fig. 2.



**Figure 2.** Block diagram of a sensor for measuring current and power  
a – with the use of a corrective amplifier ; b - without the use of a corrective amplifier

The design of the Rogovsky coil is made by a removable, single-layer winding on a dielectric frame, filled with a compound (Fig. 3). Next to the winding is a Hall sensor that duplicates the current measurement.



**Figure 3.** Placing the Rogovsky coil on the busbar:  
1 - the coil; 2 - the Hall sensor; 3 - the water-cooled busbar

To calculate the active power of the inductor in the frequency range from 30 to 50 kHz it is assumed to use the following algorithm:

1. The received signal from the Rogovsky coil goes to the correction amplifier. The correction amplifier is designed to bring the output characteristic of the sensor to a form close to linear.

2. The signal from the correction amplifier is compared in phase with the signal of the Hall sensor, which is a reference, because the Hall EMF repeats the form of the magnetic induction signal.

3. Based on the data obtained, in order to compensate for the error of phase shift of the signal at the output of the correction amplifier, a table of correction coefficients is constructed for calculating the power-frequency dependence.

4. Signals from the outputs of the correction amplifier and the load voltage divider are sent to an analog signal multiplier (i.e., AD834).

5. The signal from the multiplier is fed to a digital oscilloscope, where the average power value for the period is calculated (the instantaneous power signal is processed).

6. The received power signal is corrected according to the developed algorithm using previously obtained correction coefficients for the variable frequency.

7. The correction coefficient equation is calculated analytically depending on the frequency.

In a particular case, current and power measurements in a high-frequency power oscillating circuit, the current and voltage waveforms are almost sinusoidal. In these conditions, if the frequency range is limited, it is possible to refuse to use a corrective amplifier. Then the correction factor when calculating power will take into account both the actual current amplitude and its initial phase (Fig. 2, b).

#### 4. Numerical model of the system

Using the reference sensor in the described system is difficult, so it was decided to calibrate the measuring system using a computer model of the measurement system. When solving this problem, it was necessary to determine the value of the EMF induced on the coil of the Rogovsky coil at different frequencies, as well as the initial phase of induction near the current-conducting bus on which the sensor is installed.

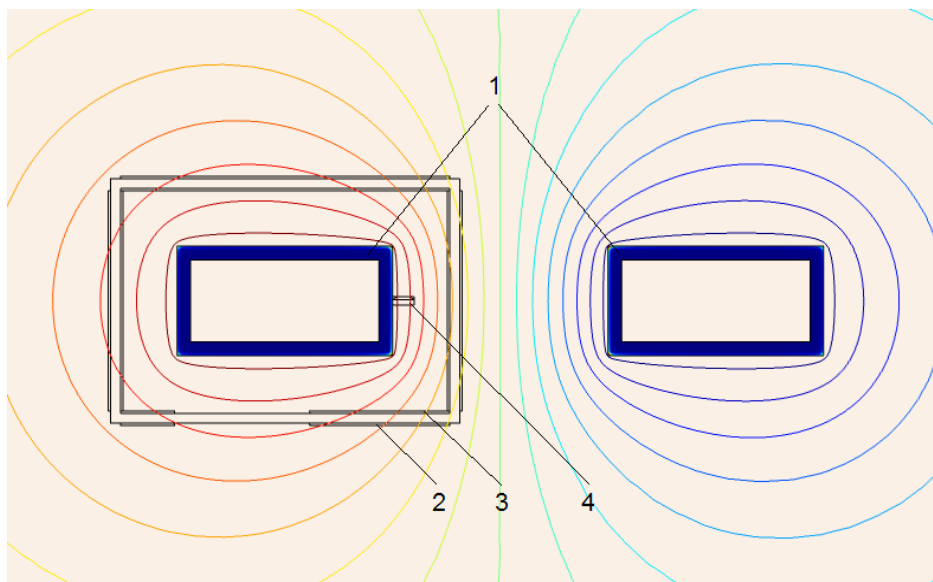
The solution of the problem of determining the parameters of the magnetic field near the current-conducting bus was carried out in a two-dimensional setting in the frequency domain (all differential field parameters change over time according to the harmonic law with a fixed frequency). Solution of the field differential equations in partial derivatives

$$\begin{cases} \frac{\partial}{\partial x} \left( \frac{1}{\mu_y} \frac{\partial A_z}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{1}{\mu_x} \frac{\partial A_z}{\partial y} \right) - i\omega\gamma A_z = -j_0; \\ \mathbf{B} = \nabla \times \mathbf{A}; \\ \mathbf{E} = -j\omega \mathbf{A}; \\ \mathbf{J} = \sigma \mathbf{E} + j\omega \mathbf{D} \end{cases} \quad (5)$$

was performed using the finite element method in the Comsol program.

The result of calculating the field for one of the frequencies is shown on Fig. 4.

When conducting numerical experiments in the range from idling to the minimum permissible load resistance of the Rogovsky coil the following values of the sensor voltages at different frequencies were obtained.



**Figure 4.** The distribution of the magnetic field near the current-conducting bus and installed sensors: 1-current busbars; 2, 3- the outer and inner sides of the Rogovsky coil coil, 4- Hall sensor.

**Table 2.** Values of measured parameters for  $I_m = 500$  A

$f$ , kHz	at $R_H = 0.1$ Ohms (short circuit)		at $R_H = 1$ MOhms (idling)	
	$B_m$ , mT	$U_{m \text{ наг.}}$ , V	$B_m$ , T	$\varepsilon$ , V
30000	6.96-0.036i	0.18049+0.010i	6.93-0.038i	-0.012+16.777i
35000	6.96-0.034i	0.18066+0.0089i	6.92-0.036i	-0.013+19.575i
40000	6.96-0.032i	0.18077+0.0078i	6.92-0.033i	-0.014+22.372i
45000	6.96-0.030i	0.18085+0.0069i	6.92-0.032i	-0.015+25.170i

The results of calculations show that when the Rogovsky coil is operating in a mode close to the short-circuit mode, the load voltage practically does not depend on the frequency, and the initial phase of the voltage does not differ from the initial phase of the current. However, in this mode, the heat output in the measuring coil becomes unacceptably high. To reduce the level of interference in the measured EMF signal from the Rogovsky coil, the load resistance should be as low as possible. For the selected conductor, the permissible current is 100 mA, and the load resistance that corresponds to this current is 256 Ohms. In table. 3. the obtained values of the voltage at a load of 256 Ohms are given, taking into account the intrinsic resistance of the coil wire.

**Table 3.** Values of measured parameters for  $I_m = 500$  A;  $R_H = 256$  Ohms

$f$ , kHz	$B_m$ , mT	$U_{m \text{ наг.}}$ , V	$I_{m \text{ наг.}}$ , mA
30000	6.93-0.037i	0.59+16.728i	65



35000	6.92-0.034i	0.81+19.508i	76
40000	6.92-0.032i	1.06+22.284i	87
45000	6.92-0.029i	1.34+25.055i	98

According to the results of the computational experiment, it can be seen that the load voltage practically does not differ in magnitude from the EMF of the coil. The maximum error is 0.3%.

the power value for sinusoidal currents and voltages can be determined by the equation

$$P = 0,5 \cdot U_m \cdot I_m \cdot \cos \varphi_2, \quad (6)$$

where  $\varphi_2$  – the difference between the initial phases of the voltage and current of the inductor.

The measured average value (the current signal is received from a corrective amplifier) of the product of the received signals (the initial power value calculated with an error when the initial phases do not match)

$$P' = k_{du} k_{dc} f \cdot \int_0^{f^{-1}} u(t) u^{imRw}(t) dt = 0,5 k_{du} U_m \cdot k_{dc} U_m^{imRw} \cos \varphi_1, \quad (7)$$

where  $\varphi_1$  – difference in the initial phases of signals received from the correction amplifier  $u^{imRw}(t)$  and voltage on the inductor  $u(t)$ ;

$k_{dc} U_m^{imRw}$  – the voltage amplitude obtained from the correction amplifier (a signal proportional to the current amplitude of the inductor);

$U_m$  – voltage amplitude on the inductor;

$k_{du}$  и  $k_{dc}$  – the coefficients of the voltage dividers for the signal of the inductor voltage and the voltage at the load resistance of the Rogovsky coil respectively.

The power value can be obtained using the correction factor  $k$ , defined using the expression

$$P = P' \cdot \frac{k(f)}{k_{dc} k_{du}}. \quad (8)$$

Then we get

$$k(f) = \frac{P}{P'} = \frac{0,5 \cdot U_m \cdot I_m \cdot \cos \varphi_2}{0,5 k_{du} U_m \cdot k_{dc} U_m^{imRw} \cos \varphi_1} = \frac{I_m \cos \varphi_2}{k_{du} k_{dc} U_m^{imRw} \cos \varphi_1}. \quad (9)$$

$$k_{Eim-l} = \frac{I_m}{U_m^{imRw}}$$

Relation it can be obtained by analyzing the results of numerical modeling and the amplitude - frequency response of the correcting amplifier, and the cosine of the angle  $\varphi_1$  using the measured values and the equation (7)

$$\cos \varphi_1 = \frac{P'}{0,5 k_{du} U_m \cdot k_{dc} U_m^{imRw}}. \quad (10)$$

In the absence of a correction amplifier in the current measurement system, the expression for determining the correction factor must take into account the changes in the



EMF of the Rogovsky coil when the frequency changes, since the signal from the coil (with the amplitude  $U_m^{Rw}$ ) enters the signal multiplier from the linear voltage divider.

$$k(f) = \frac{k_{E-I}(f) \cdot U_m^{Rw}(f) \cdot \cos \varphi_2 \cdot U_m}{P'}, \quad (11)$$

where  $k_{E-I}(f) = \frac{I_m}{U_m^{Rw}(f)}$  – coefficient that connects the voltage amplitude obtained from the Rogovsky coil with the current amplitude in the measured circuit at the frequency  $f$ .

To obtain the dependence of the coefficient  $k$  on the frequency, we will conduct a computational experiment and enter the obtained values in the table 4.

**Table 4.** Values of the measured parameters for  $I_m = 500$  A;  $R_H = 257$  Ohms

$f$ , kHz	$r_u$	$L_u$	$I_m$	$U_m$	$\varphi_2$	$\cos\varphi_2$	$P = 0,5 \cdot U_m I_m \cos\varphi_2$
30	$2.953 \cdot 10^{-3}$	$1.365 \cdot 10^{-6}$	500	1.4765+129.12i	89.345	0.011	369.1
35	$3.584 \cdot 10^{-3}$	$1.366 \cdot 10^{-6}$	500	1.7920+150.64i	89.318	0.012	448.0
40	$4.207 \cdot 10^{-3}$	$1.366 \cdot 10^{-6}$	500	2.1035+172.16i	89.300	0.012	525.9
45	$4.824 \cdot 10^{-3}$	$1.367 \cdot 10^{-6}$	500	2.4120+193.68i	89.287	0.012	603.0

$f$ , kHz	$U_m^{Rw}$	$k_{E-I} = \frac{I_m}{U_m^{Rw}}$	$P'$	$k(f) = \frac{k_{E-I} \cdot U_m^{Rw} \cos \varphi_2 \cdot U_m}{P'}$	$P = \frac{k(f) \cdot P'}{k_{dc} \cdot k_{du}}$
30	0.59208+16.815i	29.717	0.022	0.17	369.1
35	0.80922+19.610i	25.476	0.03	0.152	448.0
40	1.0598+22.400i	22.296	0.039	0.136	525.8
45	1.3436+25.186i	19.824	0.049	0.124	603.0

In the future, it is unnecessary to need to measure the true value of the angle.

## 5. Conclusions

The usage of the Rogovsky coil as a current sensor for measuring the active power of an induction installation can be justified in cases where the installation design does not provide for the installation of other sensors (based on the Hall effect and current transformers) that have a ferromagnetic core in their design. This solution can be rational if it is necessary to measure current and power in high frequency power oscillating circuits of induction heating installations.

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